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Propulsion for CubeSats

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ABSTRACT

At present, very few CubeSats have flown in space featuring propulsion systems. Of those that have, the literature is scattered, published in a variety of formats (conference proceedings, contractor websites, technical notes, and journal articles), and often not available for public release. This paper seeks to collect the relevant publically releasable information in one location. To date, only two missions have featured propulsion systems as part of the technology demonstration. The IMPACT mission from the Aerospace Corporation launched several electrospray thrusters from Massachusetts Institute of Technology, and BricSAT-P from the United States Naval Academy had four micro-Cathode Arc Thrusters from George Washington University. Other than these two missions, propulsion on CubeSats has been used only for attitude control and reaction wheel desaturation via cold gas propulsion systems. As the desired capability of CubeSats increases, and more complex missions are planned, propulsion is required to accomplish the science and engineering objectives. This survey includes propulsion systems that have been designed specifically for the CubeSat platform and systems that fit within CubeSat constraints but were developed for other platforms. Throughout the survey, discussion of flight heritage and results of the mission are included where publicly released information and data have been made available. Major categories of propulsion systems that are in this survey are solar sails, cold gas propulsion, electric propulsion, and chemical propulsion systems. Only systems that have been tested in a laboratory or with some flight history are included.

1. Introduction

CubeSats are very small satellites that are composed of 10 cm cubes (1U). While they have found significant use and development as university student projects, the capabilities of CubeSats have continually increased throughout the years. The first launch of a CubeSat can be traced back to 2000 when the Aerospace Corporation used the Orbiting Picosatellite Automatic Launcher (OPAL) to deploy two tethered Picosats [1]. Eventually, California Polytechnic State University (Cal Poly) along with Robert Twiggs developed the Poly Picosatellite Orbital Deployer (P-POD), which is used by launch providers to deploy CubeSats [2]. The standards for launching a CubeSat with a P-POD have been published and updated by Cal Poly, and these have become the accepted standards by the aerospace industry and launch providers for what defines a CubeSat [3]. The standards are easily found at the CubeSat developers website (www.cubesat.org). These standards are defined specifically for the P-POD deployer, and different standards exist for other launchers. In summary, CubeSats fit the following requirements: the 1U CubeSat must be a cube shape with each side 100-mm-long. Along a single axis, there are rails that extend the side length to 113.5 mm. This standard can be combined with itself to create 1.5U, 2U, 3U and larger CubeSats. The mass limit for a 1U CubeSat is set by the Cal Poly P-POD design specifications to 1.33 kg; however, that limit can be set higher if a launch waiver is granted [4].

Since early development and use as university training tools, CubeSats have been increasingly developed for commercial and military purposes and NASA science missions. The decreasing size of technology, combined with increased capabilities of components used in CubeSats and the low-cost of developing, building, and launching a CubeSat has led to proposals for more demanding CubeSat missions. Proposed missions include low-cost technology demonstration missions, formation flying missions that consist of swarms of CubeSats, and inspection satellites that can approach larger satellites already in orbit. To date, 1U, 1.5U, 2U, 3U, and 6U satellites have been launched, and there are proposed missions being developed with up to 12U CubeSats. The increased demands on CubeSats and their abilities have led to the need for propulsion systems onboard. These propulsion systems may be used for active attitude control, reaction wheel desaturation, drag recovery, orbit changes, interplanetary missions, and proximity operations. Required delta-V (ΔV) for proposed missions ranges on the order of m/s for ACS desaturation only missions to several km/s for interplanetary missions.

Due to the significant and growing interest in CubeSat mission

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capabilities, several propulsion systems have been rapidly developed for use on CubeSats. Because of the rapid development of technology related to CubeSats, there have been significant changes, additions, and improvements in propulsion systems. This paper first discusses the limitations to propulsion systems that are a result of the CubeSat standard, including launch restrictions. Next, necessary propulsion subsystems and performance metrics are provided to give necessary background. Then, propulsion systems will be described, categorized by the source of acceleration energy. These categories are: solar sails; cold gas propulsion systems; electric propulsion (EP) systems, including warm gas and electrodynamic tethers in addition to traditional EP systems; and chemical propulsion systems including monopropellant, bipropellant, and solid rocket systems. Examples of specific types of propulsion systems are given throughout the paper; however, these are not the only systems available. A discussion of flight history and/or flight readiness will be included for specific propulsion systems and propulsion system categories based on publically available information. Much of the data regarding individual propulsion systems come from manufacturer's websites. When available, data from peer-reviewed literature and conference proceedings are used to verify manufacturer published data.

2. Limitations of propulsion systems for CubeSats

A CubeSat must conform to several specifications and requirements for launch consideration when launching as a secondary payload. Due to the original educational nature of CubeSats, the standards for launch were designed so that CubeSats can rely on free and reduced cost launches as secondary payloads that will cause no harm to the primary launched payload [2]. While there is no mention of propulsion systems in the current version of the CubeSat Standard (Version 13), many of the requirements in the standard either directly or indirectly affect propulsion systems. Requirement 3.1.3 of the CubeSat Design Specifications states that no pyrotechnics are permitted on a CubeSat [4]. This discounts several ignition systems and all solid chemical rocket propulsion systems from launch with a P-POD without a waiver. Propulsion systems are required to have at least three inhibits (often four) in place to prevent accidental ignition or starting of the propulsion system. Furthermore, the propellant inhibits prevent leakage since many months can pass between propellant loading and launch. Usually, these consist of three independently operated valves between the propellant tank and the propulsion system to prevent the flow of propellant. An inhibit could also consist of electrical switches for the purpose of electric propulsion or deployment mechanisms for the purpose of solar sails.

Limits on the amount of stored chemical energy with which a CubeSat can be launched (100 W-Hours) significantly decrease the amount of chemical propellant that can be launched onboard a CubeSat [4]. 100 W-Hours is equivalent to 360 kJ of stored energy; this amount of energy is stored in the chemical bonds of approximately 0.019 kg of Hydrazine, a common monopropellant for spacecraft. Therefore, a waiver would be required to launch a CubeSat with sufficient amounts of chemical propellant to perform any sort of maneuver or reaction wheel desaturation. So far, no waivers to range safety have been granted for CubeSats launched as secondary payloads from P-PODS.

There are no designated upper limits on the pressure that can be stored on a CubeSat so long as the pressure remains below the maximum design pressure of the propellant tank; therefore, storage of inert propellants seems to be the most practical in terms of launch restrictions. However, the regulation that any propulsion system be designed, integrated, and tested in accordance with the Air Force Space Command Range Safety Manual (91-710), volume 3, defines systems with operating pressures greater than 100 psig as hazardous flight hardware [5]. Any component designated as hazardous hardware must undergo significant design, testing, inspection, and certification prior to acceptance by Range Safety, which is often prohibitively expensive for CubeSat systems. Other limitations are more general to CubeSats rather than specific to the propulsion system. These include the use of hazardous materials, total mass loss due to material outgassing, magnetic field strength outside the CubeSat envelope, and maximum mass of a CubeSat [4].

Due to the limitations, propulsion has only been used in a very limited manner on CubeSats. Limited flight heritage details will be discussed with each propulsion system. To date, cold gas propulsion thrusters, electrospray thrusters, and vacuum arc thrusters have been launched on the CubeSat platform. Furthermore, propellantless solar sail propulsion systems have also been launched with the CubeSat constraints.

3. Propulsion subsystems and performance

Due to size and mass restrictions, no discussion of propulsion systems for CubeSats would be complete without an introduction to some of the required subsystems and performance characteristics.

3.1. Propellant feed systems

Propellant feed systems are vitally important components of propulsion systems. When a CubeSat is launched as a secondary payload, there a several requirements dictating the types of propellants that can be carried as well as the inhibits to preventing that propellant from flowing when it is not supposed to. Thus, a discussion of propellant feed systems is necessary to this discussion of propulsion systems for CubeSats. Pressure fed systems use the pressure at which the propellant is stored to feed the propellant into the propulsion system. When the satellite is a secondary payload, range safety issues can limit the pressure at which the propellant is stored to less than 100 psig, so pressure-fed feed systems limit the amount of propellant that can be stored onboard. For a propellant that is stored in the liquid phase, the pressurization gas must be added to the propellant tank, often in a separate bladder; however, when the propellant is stored as a gas, then the pressurization gas is the propellant. Pressure-fed systems are often used with monopropellant and bi-propellant chemical propulsion systems, warm gas propulsion systems, and electric propulsion systems. Self-pressurization systems are often used with cold gas propulsion systems. The idea behind self-pressurization systems is that the propellant is stored as a liquid or solid. When exposed to heat addition or vacuum pressures, the propellant vaporizes, creating a pressure differential between the location of vaporization and the nozzle exit that feeds the propellant. Refrigerants and iodine are propellants that are often used in self-pressurization systems. Spring-fed propellant systems are commonly used for ablative electric propulsion systems. In these types of systems, as the propellant surface is ablated away, a spring pushes the propellant face forward to where the ablation occurs. Pump-fed propellant feed systems allow the propellant to be stored at lower pressures; however, they are too complex for use in CubeSat propulsion. Pump-fed systems often require a secondary gas burning system to operate the pump, and they are most often used in large launch vehicles.

3.2. Propulsion system performance

There are several methods for comparing thruster performance. Examples include thruster efficiency, specific impulse (Isp), total impulse, and impulse density. Efficiency has a variety of meanings when applied to different types of propulsion systems. For example, when discussing monopropellant systems, combustion efficiency is often used; however, for electric propulsion systems, propellant utilization efficiency might be the best way to describe how well the system converts power into thrust. Because of these discrepancies, efficiency is not the best method for comparing propulsion systems in CubeSats. Isp is the measure of the total impulse delivered per unit of propellant consumed. This parameter allows for comparison across types of propulsion systems; however, Isp does not provide any indication of the total impulse or the time required to achieve that impulse. Propulsion systems with high Isp often have very low mass flow rates, and thus require a long period of time to achieve the same total impulse as a chemical propulsion system. Therefore, satellite lifetime, which can be as short as weeks for CubeSats, plays a vital role in the comparison of propulsion systems. Total impulse will give an indication of the amount of momentum change that a propulsion system can provide; however this is also dependent on the amount of propellant that the satellite can carry. Therefore, when comparing propulsion systems by using total impulse, one must assume that the same amount of propellant is carried by each system. This assumption is not often valid because different propellants and propulsion systems have varying densities and masses. Thus, one system may have a larger mass than another, and to maintain the mass limitations of the CubeSat, less propellant can be carried with the more massive system. Impulse density is a measure of the total impulse per unit volume of the propellant. This allows for consideration of the volume limitations of CubeSats. While no single performance parameter is ideal for analyzing CubeSat propulsion systems, a combination of these performance parameters provides a good idea of the benefits and drawbacks for the various types of propulsion systems.

Dry mass is assumed to be the total propulsion system mass without propellant. Often, ΔV for a given spacecraft configuration is reported rather than Isp. Therefore, Isp was calculated using the Tsiolkovsky rocket Eq. (1).

$$\frac{\Delta V}{(Isp)g} = \ln\frac{M_o}{M_f} \tag{1}$$

where ΔV is the potential change in velocity, g is the gravitational constant of earth, M_O is the initial mass of the spacecraft, and M_f is the final mass of the spacecraft after the propellant has been used.

4. Solar sails

Solar sails utilize momentum from photons emitted by the sun to provide a propulsive force for the spacecraft. While the amount of momentum is small, if the sail is sufficiently large, a significant amount of ΔV can be gained. NanoSail-D2 was a 3U CubeSat from NASA. The satellite was the first solar sail vehicle to orbit the earth, and only the second solar sail to be deployed in space. The 10 m^2 sail was deployed on January 20, 2011. Due to the low orbit altitude, no thrust was generated; rather there was an increase in drag that caused the satellite to deorbit sooner than would be expected from NanoSail-D2's initial orbit [6].

The LightSail-A 3U CubeSat was developed by the Planetary Society to demonstrate the feasibility of solar sails. The spacecraft successfully deployed a 32 m^2 solar sail that consisted of four independent aluminized Mylar® triangular sails in 2015, shown in Fig. 1 [7]. This demonstration was only a test of the deployment system, and no thrust from solar wind could be generated because of the low altitude of the orbit. The solar sail system took up 2U of volume, 1U for the sail itself, and 1U for the deployment mechanism and booms [7]. A future mission to measure thrust is planned in LightSail2.

CU Aerospace has worked with the University of Illinois to develop the 3U CubeSail spacecraft. The satellite is a demonstrator mission for the more complex UltraSail concept. The mission will use two similar CubeSats that launch as one 3U unit. Once in a sun-synchronous orbit, detumbled, and separated, the satellites will unwind a 260-m-long, 20 m^2 reflecting film between the satellites. This concept is manifested for launch in 2017 [8].

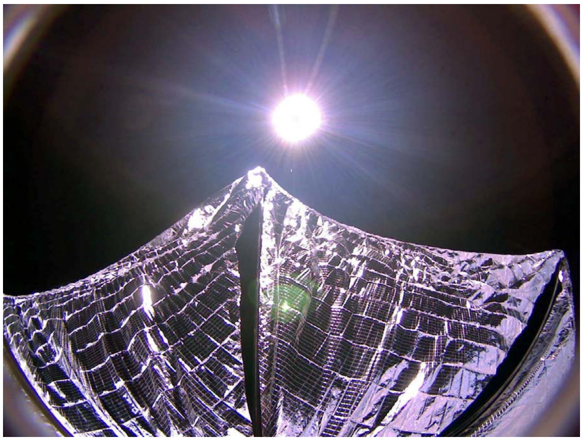

Fig. 1. Successfully deployed solar sail on LightSail-A CubeSat (Courtesy of the Planetary Society).

5. Cold gas propulsion systems

Cold gas propulsion methods accelerate the gas via a nozzle using only the available stored enthalpy without any combustion, heat addition, or other mechanism for adding energy. The propellant feed system consists of a pressure differential provided by the pressurized tank or a self-pressurization feed system between the propellant tank and the nozzle. The only required power is to control valves and provide low levels of heat to maintain minimum propellant temperature and dry wet vapor prior to being expelled through the nozzle. Because of this low power operation and simplicity, cold gas systems have flight heritage on CubeSats, and there are several more planned missions that are ready for launch. When compared with other types of propulsion systems, cold gas systems have significantly lower Isp and will deliver less ΔV for the same spacecraft because the energy stored within chemical bonds is not utilized. Several cold gas propulsion systems have been developed for the CubeSat platform, and they are the most mature type of propulsion system for CubeSats. Common propellants used for cold gas systems include nitrogen, butane, liquid sulfur hexafluoride, argon, xenon, R134a, and R236fa. Despite the maturity of the technology, little information is publically available regarding the performance of these systems on orbit. In this section, satellites that have successfully operated in orbit with cold gas systems are discussed first, and propulsion system details and operation where available are provided. Then, numerous types of cold gas systems that are available without flight heritage are discussed with specific examples from industry. All of this is summarized in Table 1.

5.1. Cold gas propulsion systems successfully operated in space

The University of Toronto Institute for Aerospace Studies (UTIAS), Space Flight Laboratory (SFL) built and flew the CubeSat, CanX-2, with a cold gas propulsion system. CanX-2 is a 3U CubeSat that launched in April 2008 with a small sulfur hexafluoride (SF_6) fueled cold gas propulsion system referred to as the Nano Propulsion System (NANOPS) [9]. The NANOPS system was designed specifically for formation flying, and performed successfully with an Isp of 46 s, a thrust of about 35 mN, and multiple starts and stops [9,11]. An updated cold gas propulsion system, the Canadian Nanosatellite Advanced Propulsion System (CNAPS) was launched by SFL on the 8U CubeSat, CanX-5. CNAPS has four thrusters and operates on SF_6 [12,13]. The propulsion system was used to perform drift recovery and station keeping [13].

The Aerospace Corporation developed a five-nozzle cold gas propulsion system for the Microelectromechanical System (MEMS) PICOSAT Inspector (MEPSI). MEPSI was not strictly a CubeSat because it did not fit the exact Cal Poly designated form factor;

Table 1
Summary of cold gas propulsion systems.

Product/ propellant	Manufacturer	Thrust	Isp	Dry Mass	Size	Flight Heritage	Ref.
NANOPS/SF_6	SFL	35 mN	46 s	480 g	5 × 5×10 cm	CanX-2	[9–11]
CNAPS/SF_6	SFL	12.5–50 mN	45 s	240 g	7 × 12.5 × 18 cm	CanX-5	[12,13]
MEMS/xenon	Aerospace Corporation	100 mN	30 s	188 g	9.1 × 9.1 × 2.2 cm	MEPSI-3	[14,15]
Micro-propulsion/argon	Microspace Rapid Pte Ltd	1 mN/ nozzle	32 s	–	–	POPSAT-HIP1	[16]
T^3-μPS/nitrogen	TNO, U. Twente, & TU Delft	6 mN	69 s	< 10 g	100 mL	Delfi-n3xt	[17–19]
MEPSI MiPS/ isobutane	VACCO	53 mN/ nozzle	65 s	456 g	9.1 × 9.1 × 2.5 cm	–	[14,20,21]
MarCO MiPS/ R236fa	VACCO	25 mN/ nozzle	–	–	–	–	[22,23]
MiPS/R134a	VACCO	10 mN/ nozzle	40 s	*542–1,245 g	0.3U–1U	–	[24]
NASA/C-POD/R134a	VACCO	25 mN/ nozzle	40 s	*1,224 g	0.8U	–	[25,26]
AFRL PUC/SO_2	VACCO	3.5 mN	47 s	434–835 g	0.25U–1U	–	[26–28]
Boeing Palomar MiPS/isobutane	VACCO	35 mN/ nozzle	–	890 g	10 × 10×10.7 cm	–	[26,29]
Custom/R236fa	U. of Texas	110 mN	64 s	290 g	10×9×4.4 cm	Bevo-2, no comms	[30]
Water propellant	Aerospace Corporation	3 mN					[31]
Microprop system/N_2 Xe, He, water, IPA	NanoSpace	0.1–1 mN	50–75 s	115 g	4.4×4.4×5.1 cm	Prisima (not a CubeSat)	[32]

* Indicates wet mass of propulsion system. Dry mass could not be found.

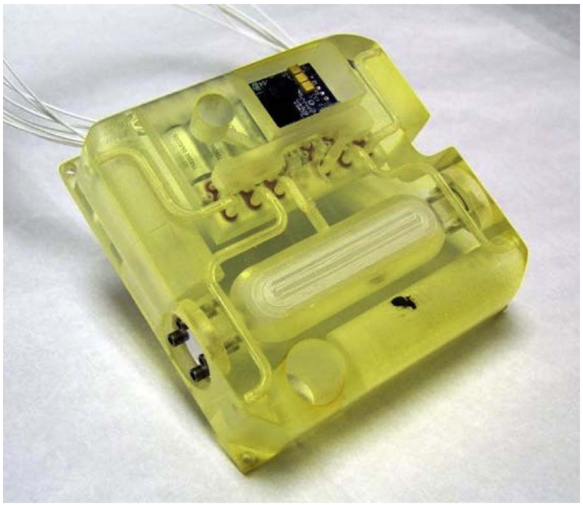

Fig. 2. Five-nozzle cold gas propulsion system developed by the Aerospace Corporation for use on MEPSI (Courtesy of the Aerospace Corporation) [14].

however, it was smaller than a 1.5U CubeSat. The propulsion system, shown in Fig. 2, was manufactured using additive rapid manufacturing so that the propellant tank, plumbing and nozzles are all manufactured out of one piece, limiting the possibility of leaking. The system operated on Xenon, and one of the five thrusters was successfully fired in 2006 following satellite deployment [14,15].

Microspace Rapid Pte Ltd of Singapore operated their eight-thruster cold gas propulsion system on the 3U CubeSat, Propulsion Operation Proof SATellite – High Performance 1 (POPSAT-HIP1), in 2014 [16]. The purposes of the propulsion system are to allow for formation flight and to provide station keeping. This cold gas system is based on proprietary micronozzle technology developed by Microspace Rapid Pte Ltd and operates on Argon that is stored in a propellant tank occupying 2U of space. Data from the spacecraft show that after an idle period of about 150 days, the propulsion system successfully performed the following maneuvers: angular velocity change, detumble, reduction of angular velocity, and attitude change along two axes. Overall, the system was able to produce about 2.25 m/s of ΔV [16].

The Netherlands Organization for Applied Scientific Research (TNO), the University of Twente, and Delft University of Technology (TU Delft) developed and flew a solid cool gas micropropulsion system onboard the Delfi-n3xt. The propellant was stored as a solid grain. Heat is applied to the grain, which then decomposes to 98% nitrogen. The gas is stored in the propellant tank before being used to produce thrust. The propellant is stored as a series of grains that are heated one by one. The system was able to successfully ignite two grains out of six on orbit before failure of the ignition system to activate the grains [17].

5.2. *Cold gas propulsion systems developed for CubeSats*

VACCO designed and manufactured a cold gas propulsion system with five nozzles for use on MEPSI-3; however, the Aerospace Corporation determined that the unit was too expensive for a technology demonstration mission and wanted to save it for a later mission [14]. Each thruster offers up to 53 mN of thrust with an Isp estimated to be about 65 s.

VACCO has designed several cold gas propulsion units for a variety of missions, and they are described in Table 1. One of these is the attitude control propulsion system for the Mars Cube One (MarCO), which is supposed to fly to Mars along with the InSight Mars lander to provide communication feedback during InSight's landing. The MarCo mission will be the first use of CubeSats beyond earth's orbit. The MarCO micropropulsion system (MiPS) has eight nozzles, each providing up to 25 mN of thrust with R236fa propellant. The thrusters are in place to provide desaturation of reaction wheels and active attitude control [22,33]. Other VACCO systems include the five-thruster standard MiPS, the eight-thruster NASA C-POD MiPS, the Air Force Research Laboratory (AFRL) Propulsion Unit for CubeSats (PUC), and the eight-thruster Boeing Palomar MiPS.

Bevo-2 is a 3U CubeSat that was deployed from a microsatellite. It has a cold gas propulsion system designed at the University of Texas at Austin with 90-g of Dupont R236fa refrigerant [34]. It was predicted to be capable of an Isp of 64 s and a thrust of 110 mN with a propellant temperature of 24 °C. When the propellant is heated to 85 °C, the Isp increases to 89 s and the thrust to 150 mN [30]. The satellite system deployed successfully from the ISS; however Bevo-2 prematurely separated from its host, and communication with Bevo-2 was never established.

Successfully launched and operated on the microsatellite Prisima, the NanoSpace micropropulsion system is a cold gas system with a form factor that will fit within a CubeSat. It has four micronozzles, and each nozzle has a thrust ranging from 0.1–1 mN. Its Isp ranges from 50–75 s, and the device requires about 2 W per nozzle. It can operate on a variety of propellants, including water, xenon, helium, nitrogen and isopropyl alcohol (IPA) [32].

6. Electric propulsion systems

Electric propulsion (EP) systems utilize onboard power to generate thrust. They generally generate less thrust and higher Isp than cold gas and chemical propulsion systems. In general, there are three types of EP systems: electrothermal, electromagnetic, and electrostatic. In addition, electrodynamic tethers are included in this section.

Electrothermal systems use electrical power to heat a gas, which is then accelerated through a supersonic nozzle, transferring propellant enthalpy into kinetic energy. These types of propulsion systems include resistojets, arcjets, radio frequency (RF) heating, microcavity discharges, and microwave heating thrusters. Resistojets use resistive heating elements to electrically heat the propellant before it is accelerated through the nozzle. Arcjets are not thought of as feasible propulsion devices for CubeSats because of the large mass, power, and thermal requirements as compared with resistojets.

Electromagnetic systems use a combination of electric and magnetic fields to accelerate plasma. These systems typically include pulsed plasma thrusters (PPTs), vacuum arc thrusters (VATs), and thrusters utilizing a magnetic nozzle.

The third category of EP is electrostatic propulsion, which often requires magnetic fields to ionize propellant, while thrust is produced through electrostatic acceleration of the plasma. Electrostatic devices include Hall thrusters, ion engines, and electrospray thrusters. Since EP requires energy to either heat or ionize a propellant, power is usually the limiting factor when trying to design an EP system for CubeSats. Furthermore, unlike chemical propulsion, traditional Hall thruster and ion engine systems do not scale very well into smaller systems. Therefore, several new concepts have been developed for use on CubeSats. The EP section will be separated by category with the addition of a section on electrodynamic tethers.

6.1. Electrothermal propulsion

Electrothermal EP is also often referred to as warm gas propulsion. These propulsion systems use electrical power to heat a propellant. For CubeSat systems, this results in a higher Isp when compared with cold gas, but, often lower than chemical propulsion systems, depending on the type of heating mechanism and available power. Electrothermal systems do not involve combustion, so they do not have as many launch limitations as chemical propulsion systems. Electrothermal propulsion systems have one documents flight on a CubeSat. The NanoSpace CubeSat MEMS propulsion module flew on the CubeSat TW-1 from China on September 25, 2015. Electrothermal systems remain a promising technology for CubeSat propulsion because it can operate with inert propellants, does not require the CubeSat to carry combustible material, and can be used with storable propellants. Furthermore, there is significant flight heritage for electrothermal systems such as resistojets for active attitude control systems on traditional satellites.

Electrothermal systems are similar in setup to cold gas propulsion systems but with an added heating mechanism. The addition of this feature provides higher performance characteristics, but it also requires a significant amount of power when compared with cold gas propulsion systems. Resistive heating is the most common method for heating, and these devices are called resistojets. Other methods for heating propellants include using radio frequency (RF) heating, micro cavity discharges, and microwave heating. Table 2 summarizes electrothermal propulsion systems that are available. So far, no electrothermal system has successfully been utilized in space on a CubeSat.

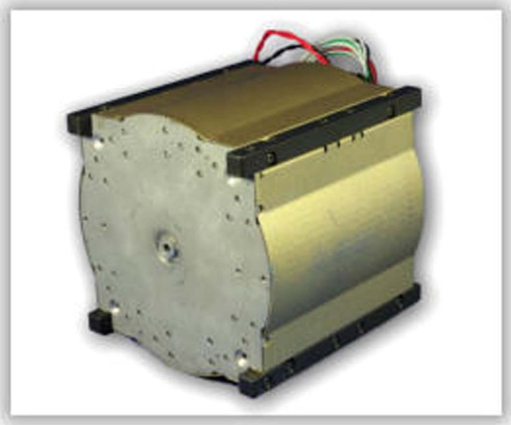

Fig. 3. Busek Company, Inc. micro resistojet propulsion module (Courtesy of Busek Company, Inc. [36].

6.1.1. Resistojet thrusters

Resistojets have a significant flight history on board several traditionally sized and even microsatellites. However, none have been flown onboard a CubeSat. CU Aerospace and VACCO have developed the CubeSat High Impulse Propulsion System (CHIPS) resistojet for attitude control and primary propulsion. The system operates on R134a, and can offer up to 82 s Isp with 30 mN of thrust operating at 30 W input power [35]. Busek Company, Inc. developed a micro resistojet thruster capable of up to 150 s of Isp and 10 mN of thrust with 15 W of operating power using ammonia as the propellant. The propulsion module, shown in Fig. 3, is about 1.25 kg and takes up 1U of space [36]. The RAMPART 2U CubeSat is supposed to launch with a resistojet propulsion system designed by Dr. Adam Huang and his graduate students at the University of Arkansas. The RAMPART propulsion system (RPS) is manufactured using rapid prototyping to fit into a 1U bus that includes a MEMS 2-phase separator and a MEMS heater and temperature sensor. The RPS uses R134a as its operating propellant, and therefore, it is capable of self-pressurization [38].

6.1.2. Other warm gas propulsion systems

The CU Aerospace/VACCO PUC system designed for AFRL can also be a warm gas system in addition to a cold gas system. It uses a micro cavity discharge (MCD) designed by CU Aerospace to heat the propellant. MCD technology uses 50–500 kHz, 500 V electrodes to heat the propellant up to 1500 K using abnormal glow discharges [39]. The CU Aerospace/VACCO MCD warm gas thruster is capable of operating on several propellants including R134a and sulfur dioxide (SO_2) [26–28]. Fig. 4 shows the CU Aerospace/VACCO PUC operating in warm gas mode on SO_2.

NanoSpace has developed a new version of their cold gas micropropulsion system and adapted it to a warm gas system. This system is shown in Fig. 5. It is called the CubeSat MEMS propulsion module. This system operates on butane propellant with four thrusters capable of up to 1 mN each and requiring 2 W of power each. According to published results, the thruster was successful onboard TW-1, but did not include the required three inhibits for launch safety. The thruster system successfully fired for five minutes. Due to the firing, the spacecraft began to spin. The spacecraft was then successfully de-

Table 2
Summary of electrothermal electric propulsion systems.

Product/ propellant	Manufacturer	Thrust	Isp	Power	Dry Mass	Size	Flight Heritage	Ref.
CHIPS/R134a	CU Aerospace/ VACCO	30 mN	82 s	30 W	–	1U+	–	[35]
Microesistojet/ammonia	Busek	10 mN	150 s	15 W	1.25 kg	1U	–	[36]
AFRL PUC/ SO_2/R134a/R236fa	CU Aerospace/ VACCO	5.4 mN	70 s	15 W	434–835 g	0.25U–1U	–	[26–28]
CubeSat MEMS system/butane	NanoSpace by GomSpace	10 μN^{-1} mN	60-92 s	2 W/ nozzle	295 g	0.44U	TW-1	[37]
RPS/134a	University of Arkansas	500 mN	–	–	–	–	–	[38]

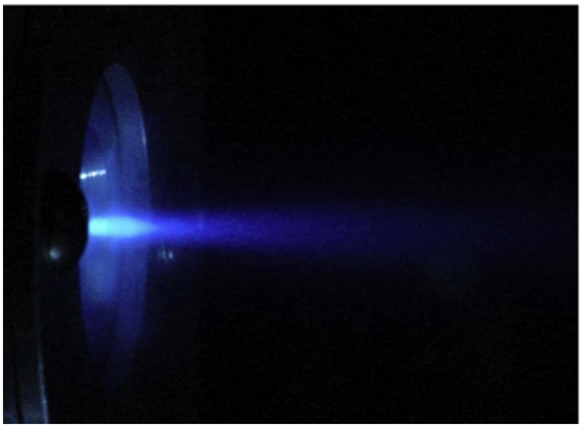

Fig. 4. CU Aerospace/VACCO Propulsion Unit for CubeSats (PUC) (Courtesy of CU Aerospace) [28].

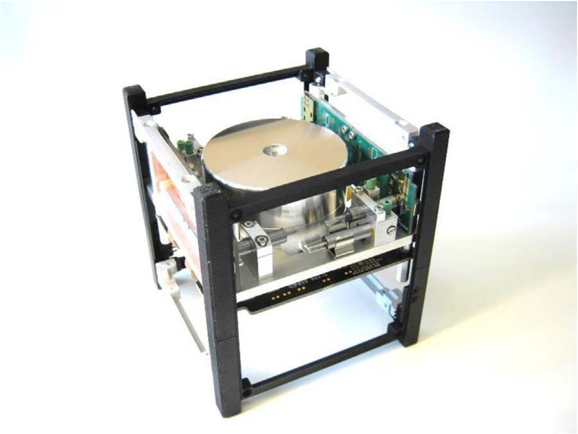

Fig. 5. CubeSat MEMS warm gas propulsion module in a 1U housing developed by NanoSpace (Courtesy of Nanospace that since October 2016 is a subsidiary of GomSpace) [37].

tumbled using the CubeSat MEMS propulsion module. The Isp ranges from 60–92 s with integrated gas heaters. There is no published information on the type of heaters, so I have not included this propulsion system with resistojets.

Another type of electrothermal propulsion system is being developed by the Space Plasma, Power and Propulsion (SP3) laboratory at the Australia National University (ANU), The electro-thermal, capacitively coupled RF plasma thruster heats propellant through ambipolar diffusion. The plasma is not used to produce thrust via electromagnetic fields, rather the hot gases are simply expanded into a vacuum without a nozzle. The thruster can operate on any number of gases because the propellant will not be in contact with any electrodes. For operation with argon, the device requires 5–40 W of input power at 13.56 MHz [40]. Only initial testing has begun, so no performance data are available.

6.2. Electrodynamic propulsion

In the area of CubeSat propulsion, pulsed thrusters such as PPTs and VATs dominate electrodynamic EP. Newer concepts such as thrusters that utilize magnetic nozzles for acceleration of the plasma are also included in this category of EP. Due to the nature of pulsed systems, it is often more applicable to list and discuss thrust in terms of impulse bit, I_b. The total amount of thrust can then be determined from the following:

$$T = fI_{bit} \tag{2}$$

where T is the thrust and f is the frequency at which the thruster can pulse. Table 3 summarizes electrodynamic systems that have been developed for CubeSats. VATs do have flight heritage on CubeSats, but results from the mission have not been released in the public domain. PPTs have significant flight heritage; however no PPT has been tested in space on a CubeSat.

6.2.1. Pulsed Plasma Thrusters

PPTs provide thrust through a series of impulse bits. A charged capacitor discharges between two electrodes, initiated by a spark igniter. The arc resulting from this discharge causes propellant to be ablated (in the case of solid propellant) and partially ionized, with the ions accelerated by self-induced Lorentz forces. The neutral particles contribute to thrust as well as they are electrothermally heated and accelerated by pressure forces [53]. Thrust levels are limited by the rate at which the capacitor can recharge. There are several types of PPTs, including solid, liquid, and gas propellant PPTs. Solid propellant is traditionally polytetrafluoroethylene (PTFE); however PTFE has a low particle mass, and there are volume inefficiencies due to feeding solid bars. In large satellites, proper design of the propellant feed system can alleviate these issues, but size and mass constraints in CubeSats limit the methods that are used in large satellites (namely more propellant). Further, spark igniter lifetime can be a problem. Liquid and gas phase PPTs offer more flexibility with respect to larger impulse bits than solid PPTs. The amount of power required to create a pulse depends on the size of the PPT and the type of propellant; liquid and gas propellants tend to require more power per pulse than solid PTFE and metal propellants. Further, the larger the impulse bit, the more power is required per pulse. PPTs tend to have an Isp of about 600–1500 s. Despite the positive aspects of PPTs, they have low efficiencies, averaging around 10% for solid propellant PPTs.

Much of the early CubeSat propulsion work focused on PPTs. The flexible power constraints, proven operation, modularity, and solid propellant make them attractive for the small form factor and range safety issues associated with CubeSats. There have been several traditional PTFE solid propellant PPTs developed for use on CubeSats. One of the first systems designed specifically for CubeSats was the Micro-Pulsed Plasma Thruster (μPPT) developed at the Austrian Research Centers GmbH that operated on PTFE. The impulse bit size for this PPT was calculated to range from 10–20 μN-s based on an estimated Isp of 1000 s [41]. Clyde Space and Mars Space Ltd. have developed a PTFE PPT for CubeSats (PPTCUP), shown in Fig. 6, that is capable of 650 s Isp with up to 45 μN-s of impulse bit operating on 2 W when pulsed at 1 Hz [42,43]. Fotec has developed a PTFE PPT module that is capable of up to 900 s Isp with impulse bits ranging from 3.5–10 μN-s [44].

Busek Company, Inc. has three pulsed power systems available that operate on PTFE propellant. Two of the systems use a micro pulsed plasma thruster, μPPT, that was developed by Busek Company, Inc. and AFRL for the FalconSat-3 satellite, a 50-kg microsatellite. The μPPT has been housed in two form factors specifically designed for CubeSats, one with 3 thrusters, and one with 9 thrusters. Busek Company, Inc.'s μPPTs have an Isp of 700 s and provide up to 0.5 mN of thrust. The 3-thruster unit has a mass of 0.55 kg and takes up a volume of 0.5U. When the thruster pulses at 2 Hz, the power required is 2 W [45]. The 3-and 9-thruster systems with flight heritage on FalconSat-3 are designed to provide active attitude control. Busek Company, Inc. has also developed a PPT system for primary propulsion. The BmP-220 can provide 0.02 mN-s impulse bits. It requires 7.5 W to operate at a frequency of 7 Hz and 1.5 W to operate at a frequency of 1 Hz. Beginning of life system mass is 0.5 kg with a volume of about 370 cm^3 [46]. The thrusters are based on the successfully flown FalconSat-3 μPPTs.

Liquid PPTs have recently been developed for small satellites that are applicable to the CubeSat standard. PPTs that operate on liquid propellant can provide more versatility by varying the amount of propellant that is ejected per pulse and can store significantly more propellant mass by using conformable tanks. However, liquid PPTs

Table 3
Summary of electrodynamic systems.

Product/ propellant	Manufacturer	Thrust/ Impulse bit	Isp	Power	Dry Mass	Size	Flight Heritage	Ref.
μPPT/ PTFE	Austrian Research Centers	10–20 μN-s	1000 s	0.5–4 W	25 g	–	–	[41]
PPTCUP/ PTFE	Mars Space Ltd.	40 μN-s	~650 s	2 W	280 g	9 × 9×2.5 cm	–	[42,43]
PPT/ PTFE	Fotec GmbH	2.5–10 μN-s	900 s	< 1 W	300 g	9 × 9×3 cm	–	[44]
μPPT/ PTFE	Busek	0.5 mN	700 s	2 W	550 g	0.5U	Falcon-Sat 3	[45]
BmP-220/ PTFE	Busek	0.02 mN-s	536 s	1.5–7.5 W	500 g	370 cm^3	–	[46]
μCAT/ metal	GWU	1–20 μN	3000 s	< 10 W	200 g	200 cm^3	BRICSat-P	[47–49]
μBLT/ Al	U of Illinois	54 μN	–	4 W	250 g	4 × 4×4 cm (PPU)	–	[50,51]
RFT xenon	Phase Four	2.77 mN	498 s	50 W	1 kg	1.2–2U	–	[52]
RFT water	Phase Four	0.44 mN	7852 s	50 W	1 kg	1.2–2U	–	[52]

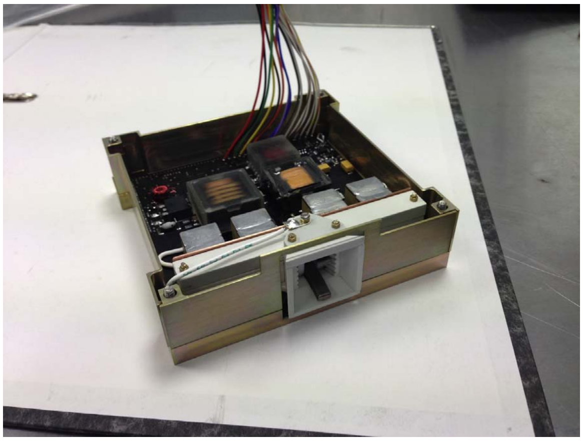

Fig. 6. PTFE pulsed plasma thruster developed by Clyde Space and Mars Space Ltd. (Courtesy of Mars Space and Clyde Space).

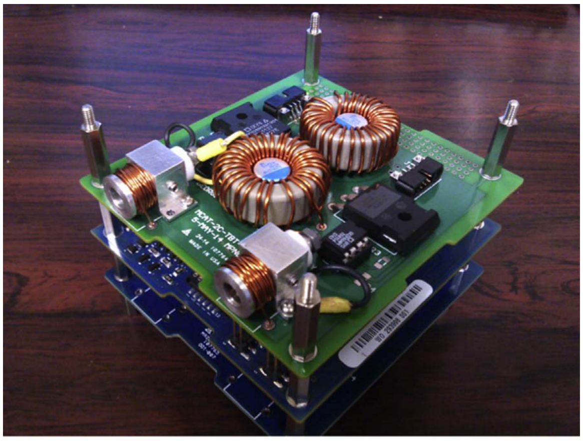

Fig. 7. George Washington University's Micro Cathode Arc Thruster (μCAT) combined with a power system for CubeSat integration (Courtesy of George Washington University).

require more complex feed systems compared with solid propellant PPTs, and it is has been proven difficult to constrain the flow of propellant to occur only when there is a pulse. The Liquid Micro Pulsed Plasma Thruster (LμPPT) being developed by QuinteScience and the Institute of Physics and Laser Microfusion in Poland operates on perfluorpolyether (PFPE), a non-hazardous liquid propellant that has traits similar to PTFE. The LμPPT has been tested in a laboratory and produced impulse bits that range from 10–25 mN-s and Isp ranging from 1000–1400 s [54].

6.2.2. *Vacuum arc thrusters*

Another type of pulsed thruster that has been developed for CubeSats is the vacuum arc thruster (VAT). VATs use vacuum arcs to produce high-velocity plasma jets directly or as sources of plasma that are accelerated electrostatically [55]. Cathode arcing during cathode spot operation creates highly ionized plasma very efficiently. The propellant comes from ablated cathode material where sputtering occurs, and therefore, no extra propellant, gas feed system, or liquid feed system are required. Because of these features, VATs have been researched heavily and several have been developed for use on CubeSats. VATs are one of the few types of thrusters that have flight heritage on CubeSats. The size of the impulse bit that can be produced by a VAT is dependent on the cathode/propellant material. VATs can use several different cathode materials, including nickel (NI), Tungsten (W), Chromium (Cr), Aluminum (Al), and Bismuth (Bi) [49,56]. Total thrust values available from VATs are low compared with other types of CubeSat thrusters, and significant ΔV required for orbit maneuvers may not be possible without several thruster heads. The very small impulse bits are ideal for precision pointing applications.

Researchers at George Washington University (GWU) have designed a VAT referred to as the Micro Cathode Arc Thruster (μCAT). This thruster differs from traditional VATs because of an applied magnetic field that causes the location of the cathode spot, and therefore propellant feed, to rotate [57]. The resulting uniform erosion of the cathode material increases thruster lifetime [58]. Fig. 7 shows the μCAT combined with a power system in the CubeSat configuration. The thruster has been successfully demonstrated on the United States Naval Academy's (USNA) BRICSat-P, a 1.5U CubeSat with four μCATs [47]. The low thrust levels are incapable of providing sufficient ΔV to perform orbit maneuvers, but the thrusters were able to de-tumble the spacecraft from rotation rates estimated at 15 deg/s to 1.5 deg/s in less than 48 h [47]. Current research on the μCAT at GWU is focused on increasing thrust-to-power ratios by using different materials for the cathode/propellant and the anode [48]. Currently, the thruster is capable of reaching up to 20 μN with 3000 s of Isp [49].

The Illinois Observing Nanosatellite (ION) was a 2U CubeSat from the University of Illinois that had four micro vacuum arc thrusters that were assembled into a sandwich configuration referred to as μBLTs. The system provided translation and two-axis rotation. The propellant was aluminum, so the spacecraft structure could be used as the propellant. The thruster was expected to provide 54 μN of thrust when operating at 4 W [50]. The thrusters were never tested in space because the launch vehicle that was carrying ION failed.

6.2.3. *Magnetic nozzle systems*

Phase Four is developing an electrodeless, permanent magnet, helicon thruster called the Radio Frequency Thruster (RFT) that is capable of operating on several propellants including xenon, iodine, and water. This thruster was specifically designed with the constraints of CubeSats in mind. The thruster has been operated in a vacuum chamber; however, only indirect thrust measurements have been reported. Predicted values for thrust and Isp when operating on xenon are between 0.5 and 4 mN and between 400 and 800 s, respectively [59]. The predicted values for thrust and Isp will vary widely depending on the propellant selected. Indirect thrust measurements give values ranging from 130 to 180 μN, but thermal issues at the time of testing

Table 4
Summary of electrostatic systems.

Product/ propellant	Manufacturer	Thrust	Isp	Power	Dry Mass	Size	Flight Heritage	Ref.
BET-1 mN	Busek	0.7 mN	400–1300 s	15 W	1.15 kg	8.5 × 8.5 × 6 cm	–	[61]
BET-100	Busek	5–100 µN	1800 s	5.5 W	–	9 × 9×4 cm	–	[62]
SiEPS (8 thruster unit)	MIT	74 µN	1150 s	1.5 W	100 g	0.2U	Aero-Cube-8 IMPACT	[63]
MiXI/ xenon	JPL	0.4–1.5 mN	1760–3100 s	14–50 W	200 g	–	–	[56,64]
µNRIT-2.5	Astrium	50–500 µN	360–2850 s	12.5 - 35 W	210 g	–	–	[65,66]
BIT-1/ xenon, iodine	Busek	100–180 µN	2150–3200 s	10–55 W	53 g[*]			[67,68]
BIT-3/ xenon, iodine	Busek	0.6–1.1 mN	1200–2000 s	55–75 W	1.5 kg	2U	–	[69,70]

[*] thruster mass only, does not include power processing unit

prevented direct thrust measurements from being made [60]. Table 3 gives two lines for the RFT to frame possible operating parameters based on xenon and water propellant that mark the high and low thrust and Isp conditions [52].

6.3. Electrostatic propulsion

Electrostatic EP systems have a wide range of acceleration mechanisms, propellant options, and operating parameters. For CubeSats, these include electrospray thrusters and ion engines. Table 4 gives a summary of electrostatic EP systems that have been developed or are in development for CubeSats.

6.3.1. Electrospray thrusters

Electrospray thrusters operate by feeding propellant to an emitter where a strong electric field is generated between the emitter tip and an opposing electrode. The propellant is distorted by the electric field and surface tension into a Taylor cone at the tip of the emitter, resulting in a further intensified electric field. There are two types of electrospray thrusters, defined by the method of emission. Colloid thrusters rely on droplet emission from the Taylor cone, while field emission electric propulsion (FEEP) thrusters rely on ion emission. Electrospray thrusters do not require the generation of a plasma discharge, and the emitter tips are in the micrometer scale range. Therefore, these devices are ideal for the types of miniaturization required for CubeSats [71].

Busek, Inc. has flown a colloid thruster onboard the European Space Agency's LISA Pathfinder (ST-7) mission. Although not a CubeSat, the thrusters have been operated on orbit. Since delivery of the ST-7 thrusters in 2008, development has continued on colloid electrospray thrusters at Busek Company, Inc. The Busek Electrospray Thruster 1 (BET-1) is a 0.7 mN device that requires 15 W of input power to deliver an Isp from 400 s to 1300 s [61]. Another electrospray propulsion system from Busek Company, Inc. is the BET-100. This 100 µN thruster requires 5.5 W and operates with an Isp of 1800 s [62]. The design and many of the components of the BETs are based on the flight heritage gained from ST-7; however, these thrusters do not have flight heritage themselves.

The Aerospace Corporation launched AeroCube-8, also referred to as the IMPACT mission. The mission, launched in 2015, consists of two 1.5U CubeSats [72,73]. The ionic liquid FEEP electrospray thrusters onboard Aerocube-8 are part of the Scalable ion Electrospray Propulsion System (SiEPS) developed by the Massachusetts Institute of Technology (MIT) shown in Fig. 8. The thrusters require MEMS based technology to machine the emitters. They are modular to provide scalable operation. In the AeroCube-8 mission, the propulsion system consists of an 8-thruster unit capable of providing 74 µN of thrust at 1150 s of Isp [63]. Although these thrusters were launched on the AeroCube-8 mission, no information regarding the operation on orbit has been presented the public domain.

There are several other electrospray thrusters that are being developed for use as propulsion systems on CubeSats. These include an indium FEEP thruster being developed at JPL [75]. The benefit of using indium propellant is that it is solid at room temperature, non-toxic, non-corrosive, has low vapor pressure, and has a relatively low melting point (154 °C) [56]. Another promising focus area for electrospray research is occurring at Michigan Technological University where ionic liquid ferrofluids are being investigated as a propellant option [76]. These unique liquids can form peaks using only an applied magnetic field. No longer requiring emitter tips greatly simplifies the manufacturing required to produce electrospray thrusters.

6.3.2. Miniature ion engines

Ion engines utilize an electrostatic field between a positively biased and a negatively biased grid to accelerate ions to very high velocity. This is an efficient method for creating thrust. There are two main types of ion engines that are differentiated by the ionization method: DC electron bombardment and RF ionization. DC ion engines typically have lower electron energy cost than their RF counterparts; however, they require more components. DC ion engines require a cathode to produce electrons, which in turn will ionize the propellant within a discharge chamber that is surrounded by magnets. RF ion engines utilize a coil wrapped around the discharge channel creating an azimuthally oscillating electric field to create plasma. An additional complication for RF ion engines is the need to convert DC power from solar panels into RF power for the thruster.

Initially, ion engines were miniaturized to provide a solution for precision formation flying. Therefore, several small ion thrusters have been designed, built, and tested. Many of these can be applied to CubeSats. Ion thrusters require a secondary neutralization cathode so that the plasma plume is neutrally charged, and this added complexity makes them less appealing for use on CubeSats. Ion engines benefit from the ability to operate on several propellants such as xenon, argon, and iodine.

The JPL designed DC discharge, Miniature Xenon Ion Thruster (MiXI) requires between 14 and 50 W of power to operate [64]. This places MiXI at the upper limit of what 3U or less CubeSats can generate. MiXI was developed before the rise of CubeSats, and thus focus was not on creating a propulsion system that would operate within CubeSat restrictions. Therefore, size and volume constraints were not considered.

European researchers have focused on miniature RF ion thrusters. University of Giessen and Astrium designed and built a 2.5-cm-diameter micro RF ion thruster (µNRIT-2.5) for formation flying purposes. The thruster is capable of thrust between 50 µN and 500 µN, at an Isp between 360 s and 2850 s operating at RF power between 12.5 W and 35 W [65,66]. Busek Company Inc. has developed a 1-cm RF ion thruster (BIT-1) and a 2.5-cm RF ion thruster (BIT-3). The BIT-3 was designed for a 3U or larger CubeSat, and the BIT-1 is a miniaturization of the BIT-3. The BIT-1 requires about 10 W of RF power to operate the thruster to provide about 100 µN of thrust at an Isp of about 2150 s [67,68]. The BIT-3 is scheduled to launch aboard two 6U deep space CubeSats for operation with iodine propellant [69]. It requires between 55 and 75 W of input power for the whole system (including neutralizing cathode), so operation will require deployable and highly efficient solar panels. Thrust and Isp have been measured with xenon propellant at between 0.65 and 1.15 mN and 1200 and

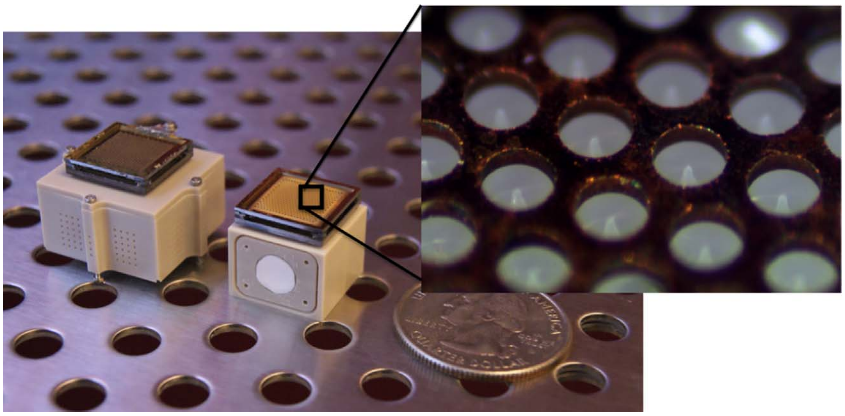

Fig. 8. Scalable ion Electrospray Propulsion System (SiEPS) developed by the Massachusetts Institute of Technology [74].

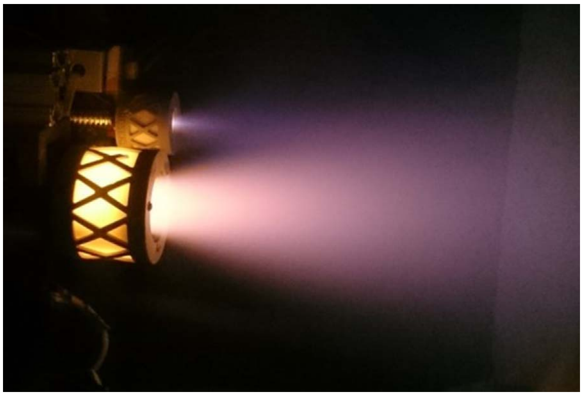

Fig. 9. Busek Company, Inc. 2.5-cm RF ion thruster (BIT-3) operating on iodine propellant with an RF neutralizing cathode (Courtesy of AIAA and Busek Company, Inc.) [69].

2000 s, respectively [69]. For the scheduled missions, the BIT-3 is suppose to use a Busek Company Inc. designed 1-cm diameter RF neutralizing cathode, also operating on iodine propellant. Both the BIT-3 and the cathode can be seen operating on iodine in Fig. 9.

6.4. Electrodynamic tethers

Electrodynamic tethers have been researched for decades as a means to provide ΔV for spacecraft orbit maneuvers without requiring onboard propellant. They utilize crossed electric and magnetic fields to induce a perpendicular force. The magnetic field comes from the earth's magnetic field, and the electric field comes from a flowing current though a tether. This force can be used for deorbit or orbit raising maneuvers. Tethers cannot be used for attitude control or relative motion between satellites [56]. Some CubeSat missions to test tethers have been launched, but none have successfully deployed a tether fully [77,78]. Missions performed with larger satellites have had more success. There is currently one propulsion system that has been designed to utilize electrodynamic tether propulsion, the CubeSat Termination Tape from Tethers Unlimited, Inc. The module has a mass of 83 g and a volume of 100 mm × 83 mm × 6.5 mm [79].

7. Chemical propulsion systems

Chemical propulsion systems use the chemical energy stored within a propellant to create propulsion. When the propellant is burned, the molecular bond is broken and energy is released in the form of an increased propellant temperature. The reaction products are then accelerated to produce thrust through a supersonic nozzle. Within the chemical propulsion category, there are several options, including monopropellants, bi-propellants, and solid rockets. The combustion process that allows the chemical energy to be utilized in chemical propulsion creates complications when trying to launch a CubeSat as a secondary payload due to limits on pyrotechnics and stored chemical energy. Therefore, while many systems are under development, no CubeSat with a chemical propulsion system has been launched.

7.1. Monopropellant chemical propulsion

Hydrazine monopropellants are the most commonly used type of chemical propulsion for in-space missions. This is because of the significant flight heritage, simplicity of the propellant delivery system, and relatively high Isp. However, hydrazine is toxic and handling requires significant safety precautions [80,81]. Therefore, using hydrazine as a propellant can be expensive. Furthermore, additional inhibits are required for hydrazine propulsion systems because of the possibility of auto-combustion at room temperature and pressure. Use of hydrazine requires a self-contained atmospheric protective ensemble (SCAPE) suit and significant operational oversight. The increased safety requirements and inhibits to accidental combustion often makes using hydrazine prohibitively expensive for CubeSats, which tend towards low-cost build, launch, and flight operations with a “do no

Table 5
Summary of chemical propulsion systems/thrusters for CubeSats.

Product/ propellant	Manufacturer	Thrust	Isp	Dry Mass	Size	Flight Heritage	Ref.
MPS-130/ HAN-based	Aerojet Rocketdyne	1 N	244 s	1.3 kg	1U[*]	–	
BGT-5X/ HAN-based	Busek	0.5 N	220–225 s	1.24 kg	1U	–	[81–83]
BGT-1X/ HAN-based	Busek	0.1 N	214 s	–	–	–	[84]
μprop system/ ADN-based	VACCO/ECAPS	0.1 N	258 s	0.9 kg	0.5–1U	–	–
LMP-103S/ ADN -based	ECAPS	0.1 N	> 200 s	–	–	–	[85]
MPS-120/ hydrazine	Aerojet Rocketdyne	1 N	225 s	1.3 kg	1U[*]	–	[81–83]
Hydros/ water	Tethers Unlimited, Inc.	0.25–0.6 N	258 s	0.5–1 kg	0.5–1U	–	[86]
CDM-1/ AP/HTPB	DSSP	76 N	226 s	460 g	152 cm^3	–	[87]

[*] Volume does not include flight electronics

harm” concept as secondary payloads on launch vehicles. As a result, alternatives to hydrazine such as green monopropellants that have been developed are being integrated into propulsion systems for CubeSats. Table 5 summarizes the chemical combustion propulsion systems including green monopropellant, hydrazine monopropellant, bipropellant, and solid propellant systems.

7.1.1. Green monopropellant

Green monopropellants, or non-toxic propellants, provide an alternative monopropellant to hydrazine. Launch and safety requirements mandate fewer inhibits with the non-toxic monopropellants as opposed to hydrazine because of low volatility at atmospheric pressures and very low vapor pressure at standard temperature when compared with hydrazine. Two of the most flight-ready non-toxic monopropellants are discussed here: hydroxylammonium nitrate (HAN)-based, and ammonium dinitramide (AND)-based propellants. These non-toxic monopropellants have higher density, thrust, and performance than hydrazine. They also burn at increased temperatures, resulting in higher Isp than hydrazine. However, due to the higher combustion temperature, development of a catalyst that can withstand the elevated temperatures has been slow. Further limiting development is that catalytic non-toxic monopropellants cannot reliably achieve ignition below 250 °C. This means that a satellite with a non-toxic monopropellant will require about three times the preheat power as a conventional hydrazine monopropellant thruster [88]. Managing thermal loads and power are key factors in CubeSat development that make integration of a non-toxic monopropellant system with a CubeSat difficult.

There are two main variants of non-toxic monopropellants on which development of propulsion systems for CubeSats has focused: HAN-based and ADN-based monopropellants. HAN-based AF-M315E is a propellant developed by the Air Force Research Laboratory (AFRL) in 1998. There is no flight heritage for AF-M315E; however, there is a planned mission under NASA's Green Propulsion Infusion Mission (GPIM). The ADN/water/fuel mixture, LMP-103S has flight heritage in the 1-N-thruster range on board the PRISIM spacecraft that could be adapted for CubeSat propulsion [89]. Both HAN- and ADN-based monopropellants have an Isp of around 250 s. HAN mixtures have a 50% increase in density-specific impulse over hydrazine, and ADN mixtures have a 30% increase in density-specific impulse [88].

Table 5 summarizes nontoxic monopropellant propulsion systems that are being designed for CubeSats. The CubeSat Modular Propulsion System (MPS) from Aerojet Rocketdyne (also referred to as the CubeSat High-Impulse Adaptable Monopropellant System- CHAMPS) is a modular propulsion system that targets small spacecraft. Aerojet Rocketdyne has adapted its MPS for HAN-based monopropellants. The MPS-130 consists of four 1-N thrusters with an Isp of about 244 s [82]. The system is in the development stages with many specifications still to be determined. Another example of a small nontoxic HAN-based monopropellant system is from Busek Company, Inc. The BGT-5X, shown in Fig. 10, is a 0.5 N thruster that can be packaged with a microvalve, propellant tank, and propellant management system into a 1U volume [90,91]. The system requires 15 W of power to heat the catalyst [84]. Busek Company, Inc. has also developed a 0.1 N thruster, the BGT-1X. VACCO has partnered with ECAPS, a subsidiary of the Swedish Space Corporation (SSC) specializing in ADN-based monopropellant thruster systems [89,92,93]. They have developed a CubeSat subsystem which consists of four 0.1 N thrusters that operate on ADN-based propellant [85]. ECAPS also offers a thruster that operates on a blended mixture of ADN called LMP-103S. This thruster has been chosen for the Lunar Flashlight mission [86]. Despite several advances and efforts by aerospace propulsion companies, no CubeSat has been launched to date with a green monopropellant system.

7.1.2. Hydrazine Monopropellant

Despite the previously mentioned limitations to hydrazine, there are several hydrazine propulsion systems that are designed for small spacecraft that could be used on a CubeSat or have been modified for use on a CubeSat. None of these systems have flight heritage on a CubeSat, and there are no published planned CubeSat missions with hydrazine propulsion systems. Aerojet Rocketdyne has a variant of its MPS thruster system that utilizes hydrazine propellant, the MPS-120. Each MPS module consists of four 1 N thrusters and takes up a volume of 1U. The hydrazine variant has an Isp of approximately 225 s. The thrusters themselves have been adapted to provide high-thrust impulse maneuvers for CubeSats from attitude control thrusters for larger spacecraft. Therefore, the technology is well established, but implementation into a CubeSat is still required. The MPS-120 is shown in Fig. 11.

Other thrusters of similar size exist to those used on the Aerojet Rocketdyne MPS system; however, they have not been integrated into a propulsion system. Moog ISP and Airbus Defense and Space both offer

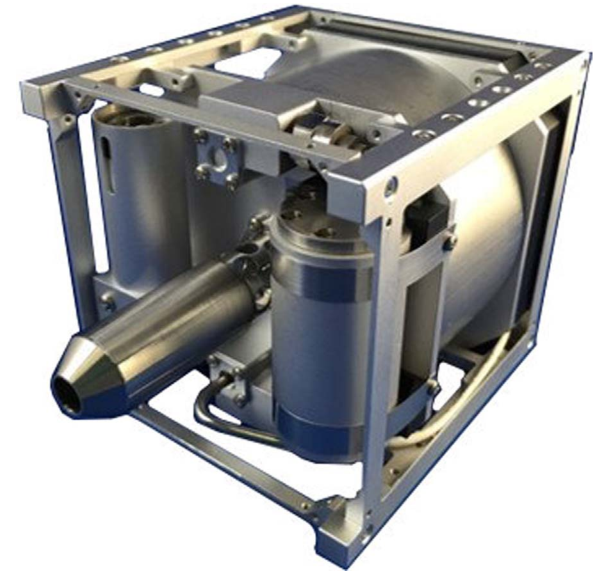

Fig. 10. Busek Company, Inc. HAN-based monopropellant thruster, BGT-5X (Courtesy of Busek Company, Inc.).

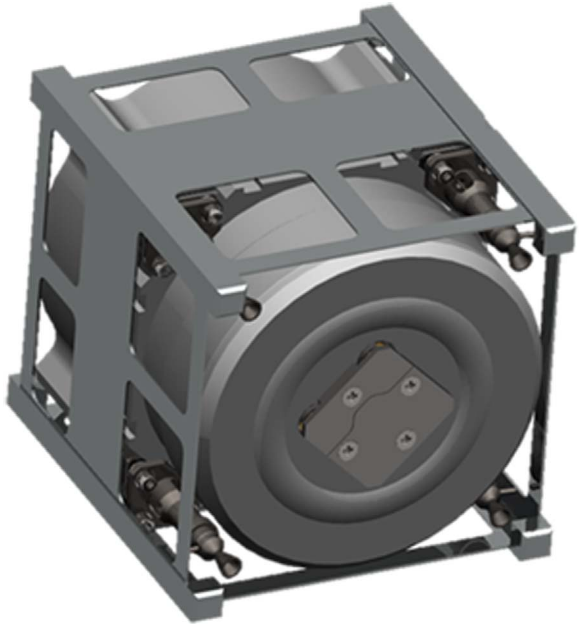

Fig. 11. Aerojet Rocketdyne developed CubeSat Modular Propulsion System variant (MPS-120) developed for use with hydrazine monopropellant (Courtesy of Aerojet Rocketdyne).

1 N class hydrazine thrusters with similar performance to those from Aerojet. Moog ISP has developed a concept for at 4-thruster system that would be the size of a 1U CubeSat [94].

7.1.3. Peroxide and peroxide blends monopropellant

Also of interest to the CubeSat community are peroxide monopropellant blends. Peroxide blends are significantly safer than hydrazine monopropellants, are easy and inexpensive to acquire, and have significant flight heritage in bipropellant thrusters [95]. Peroxide must be premixed with alcohol to allow for combustion when it encounters a catalyst, and the mixture must not combust without exposure to the catalyst, while still providing sufficient Isp to replace hydrazine or other green monopropellants. CU Aerospace has developed a mixture of peroxide and ethanol that is stable at high temperatures and during storage, but will react when exposed to a catalyst [95]. However, due to the low maturity of this technology, many launch providers and satellite owners will not currently consider launching with peroxide blends as the propellant on a secondary payload. For a CubeSat with a designated launch vehicle, the technology still requires maturation before full systems are ready for implementation into CubeSats. The lower flame temperatures, minimum toxicity, and ease of acquisition do make peroxide blends a promising monopropellant for CubeSat use.

7.2. Bi-propellant

In general, bi-propellant systems, which consist of separate oxidizer and fuel components, are not used or designed for CubeSat use. This is due to the complexity, repetition of components, and inhibit requirements of bi-prop systems. Bi-prop systems require two propellant feed systems, two propellant tanks, and twice the inhibits as monopropellant systems. Furthermore, ignition method must be considered with bipropellants, as propellants may be hypergolic (they auto-ignite upon mixture) or require an active ignition system. Both of these scenarios will cause safety issues with the storage of propellant. CubeSats are designed to be simple, low-cost satellites, and bi-prop systems add too much complexity and cost. One exception to this is the HYDROS system by Tethers Unlimited, Inc, shown in Fig. 12. The HYDROS thruster uses electrolysis to convert water into hydrogen and oxygen. Then, the two gases are combusted in a bipropellant thruster. Benefits of this system are that only one propellant tank is required for the water, and no ignition inhibits are needed because the propellant is not combustible on its own. However, the added complexity, cost, and mass of the water electrolyzer must be accounted for. Additionally, the system requires power to operate the electrolyzer. The system comes as a 0.5U or a 1U unit. Thrust was measured to range between 0.25 N and 0.6 N with an average Isp of 258 s [96]. The mass of a 0.5U system is about 0.5 kg, and the mass of a 1U system is about 1 kg. The power required to operate the Hydros propulsion system varies from 5–10 W depending on the required thrust.[1]

7.3. Solid propellant

Solid chemical propulsion systems have not been extensively developed for CubeSats due to the CubeSat Standards limitations on pyrotechnics. Despite that, some systems do exist. Digital Solid State Propulsion (DSSP) has developed the CDM-1 solid rocket system that can provide up to 50 m/s of ΔV to a 4-kg, 3U CubeSat. The system operates on AP/HTPB, an ammonium perchlorate composite propellant. The Isp is 235 s with an average thrust over the burn time of 76 N and a maximum thrust of 186 N. The total mass of the system, including propellant is 450 g, and the volume is 152 cm^3 [87]. The amount of thrust provided by the small solid rocket motor is significant for a CubeSat, and the satellite would begin to significantly tumble without a robust attitude control system. Therefore, solid rockets, if used would be best served as a de-orbit mechanism.

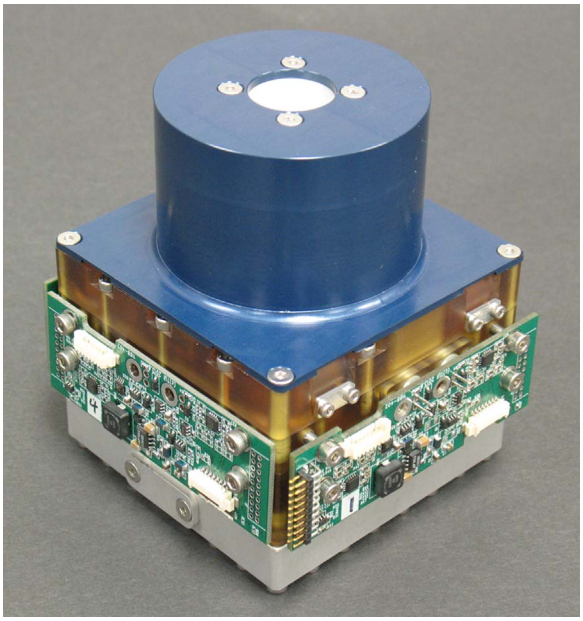

Fig. 12. HYDROS thruster from Tethers Unlimited, Inc. (Courtesy of Tethers Unlimited, Inc.)

8. Summary and conclusions

Propulsion systems are required to continue the rapid growth and increased mission capability of CubeSats. However, due to limitations in the CubeSat platform itself, advancement of these systems from concept to flight heritage is slow. Less than 10 CubeSats have flown with propulsion systems, and the majority of those have used cold gas systems. Flight data from more complex systems that have launched, such as the μCAT from George Washington University and SiEPS from MIT, are limited or not available in publically released literature. Significant study into the integration of propulsion systems with CubeSat infrastructure is required. Electromagnetic interference from power processing units, and thermal management issues from chemical and EP systems will need to be eliminated before attempted flights. Current efforts seem to focus on larger versions of CubeSats with 12U busses in efforts to mitigate thermal and EMI issues. The larger size also allows for more propellant. However, this solution is not appropriate for CubeSat missions with goals of smaller, less expensive spacecraft. Novel propulsion ideas will continue to push research and CubeSat capabilities; however, one should not lose focus on the effort to achieve propulsion systems for CubeSats that can provide flight heritage.

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